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Power Management for Energy Systems

Tobias Gybel Hovgaard[1,2], Lars F. S. Larsen[1], Morten Skovrup[3], Stephen Boyd[4], and John B. Jørgensen[2]

1) Vestas Technology R&D, Aarhus N, Denmark.

2) Dept. of Applied Mathematics and Computer Science, Technical University of Denmark.

3) IPU Technology Development, Denmark.

4) Stanford University

*) In collaboration with: Danfoss A/S, Electronic Controls R&D, Denmark.

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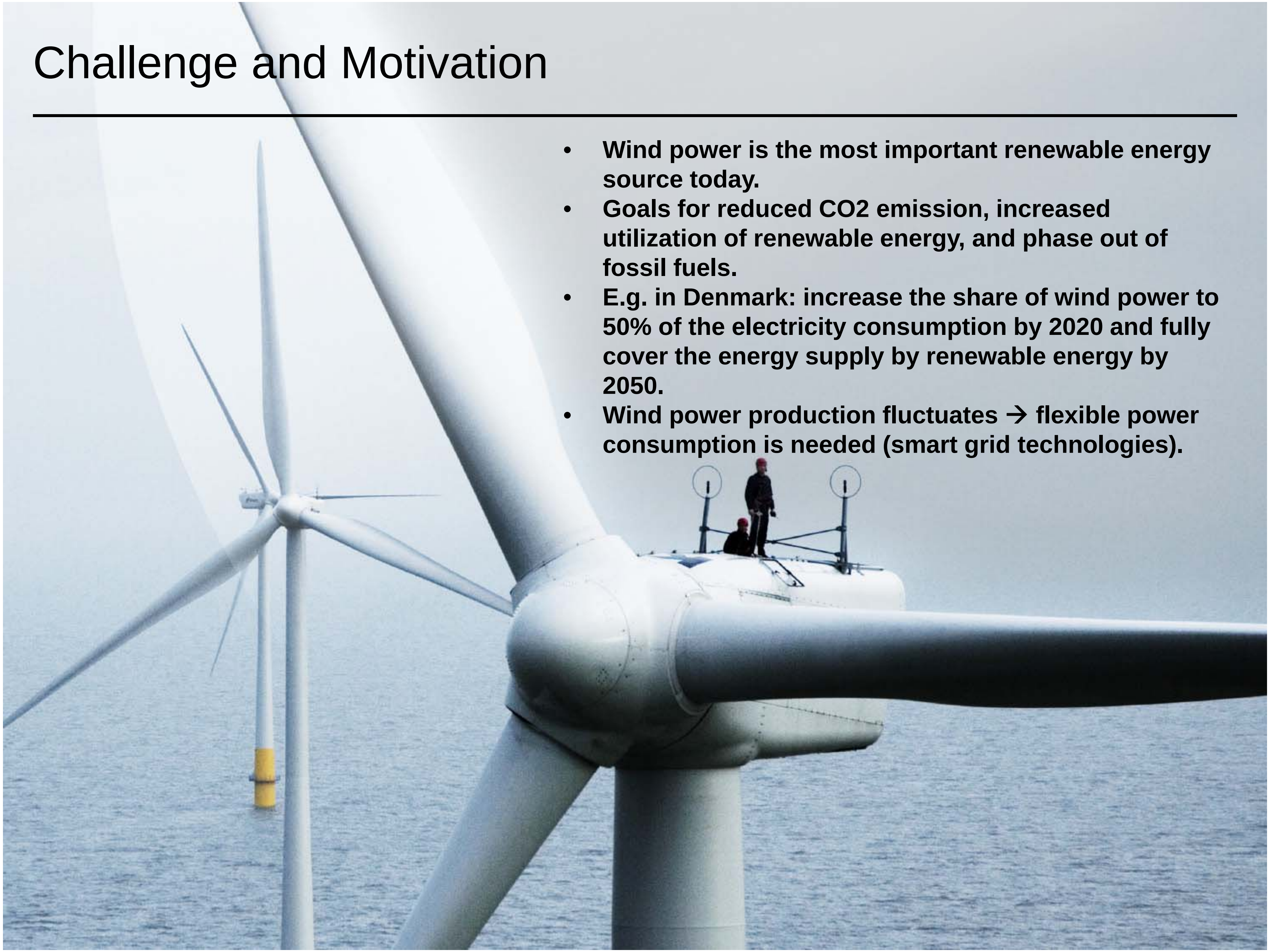
Challenge and Motivation

- **Wind power is the most important renewable energy source today.**
- **Goals for reduced CO_2 emission, increased utilization of renewable energy, and phase out of fossil fuels.**
- **E.g. in Denmark: increase the share of wind power to 50% of the electricity consumption by 2020 and fully cover the energy supply by renewable energy by 2050.**
- **Wind power production fluctuates → flexible power consumption is needed (smart grid technologies).**

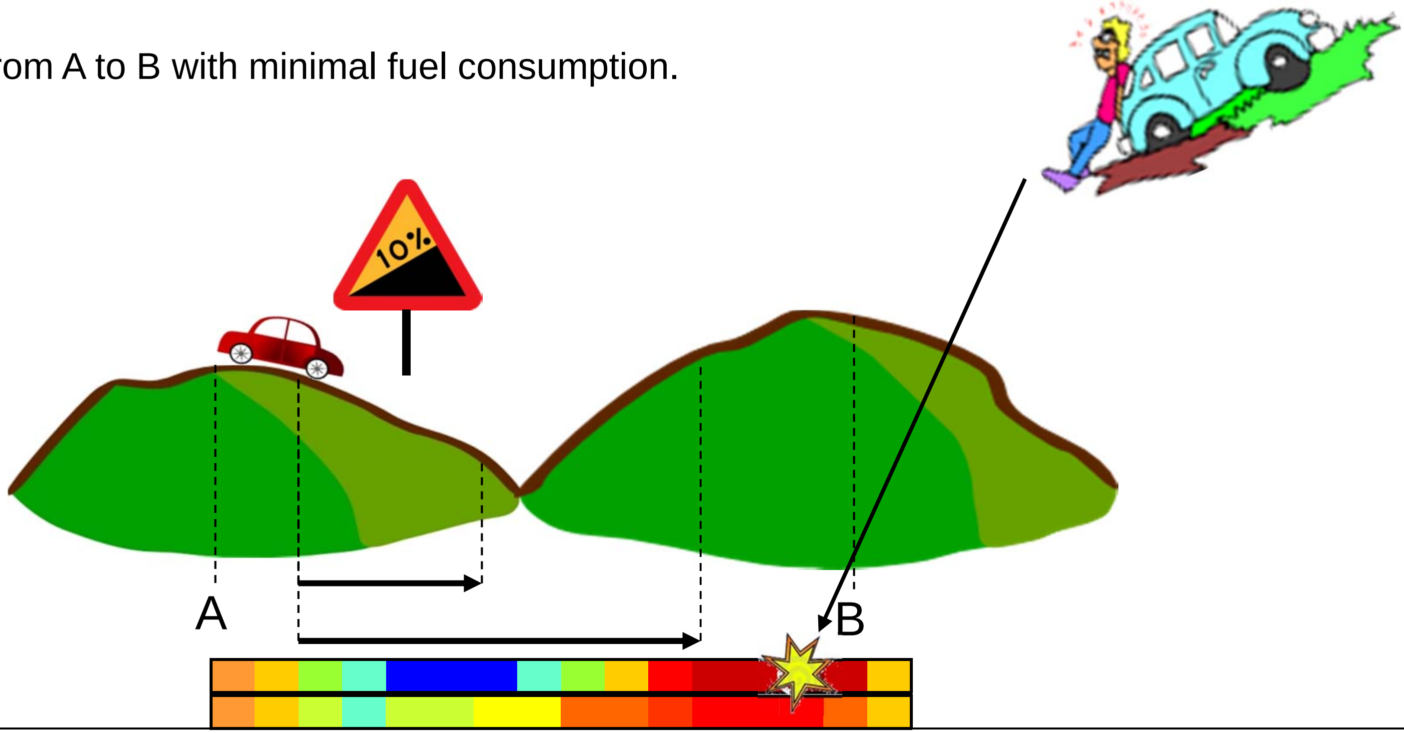


Utilizing Thermal Mass

Intelligent load-shifting and scheduling by storing “coldness” for:

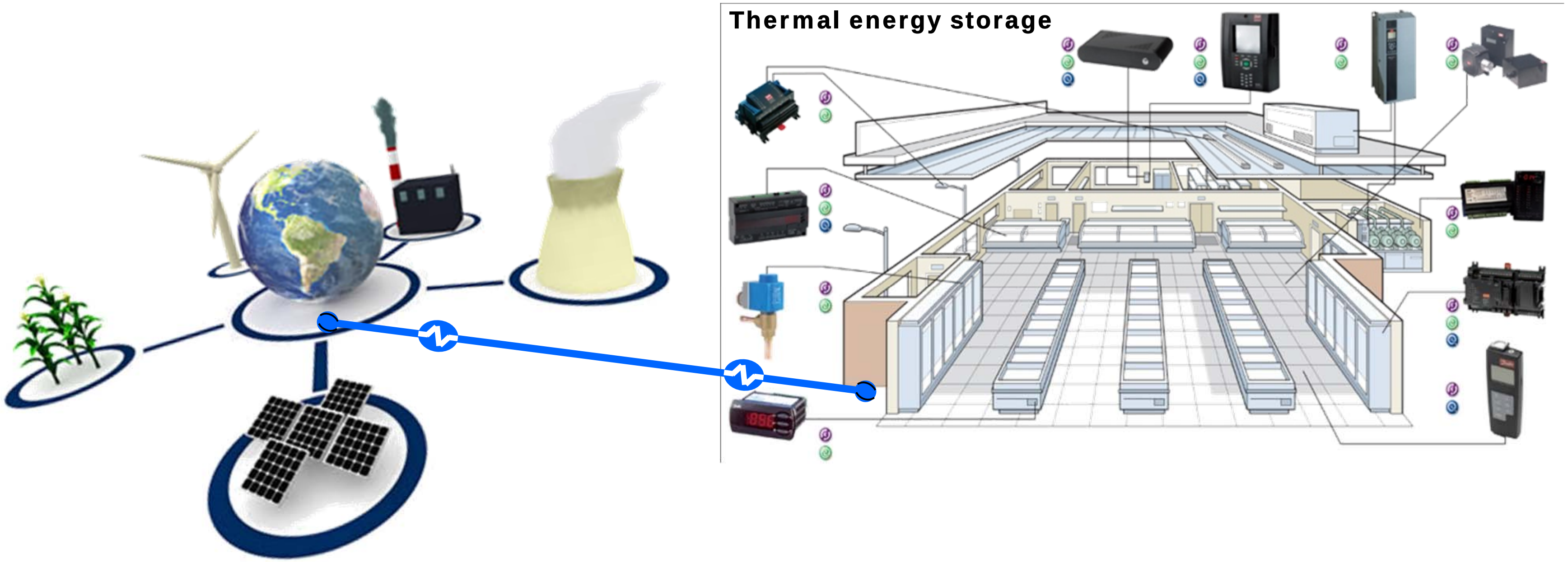
- Peak avoidance (foreseeing peaks can reduce dimensioning of the system)
- Minimal power consumption (Cooling at colder periods is more efficient)
- Minimal cost (Energy prices may vary over the day)
- Flexible consumption (More renewable energy calls for flexible power consumption)

Example: Drive from A to B with minimal fuel consumption.



Power Management

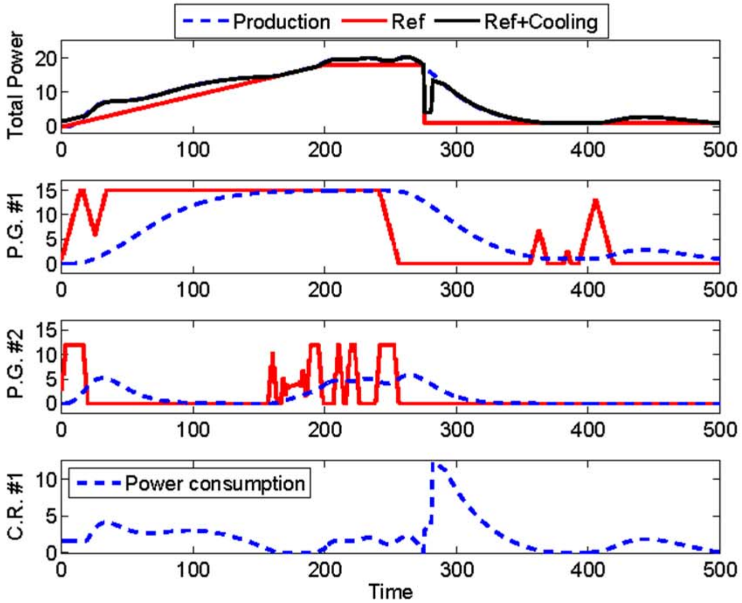
Example: Smart Grid (Flexible consumption).

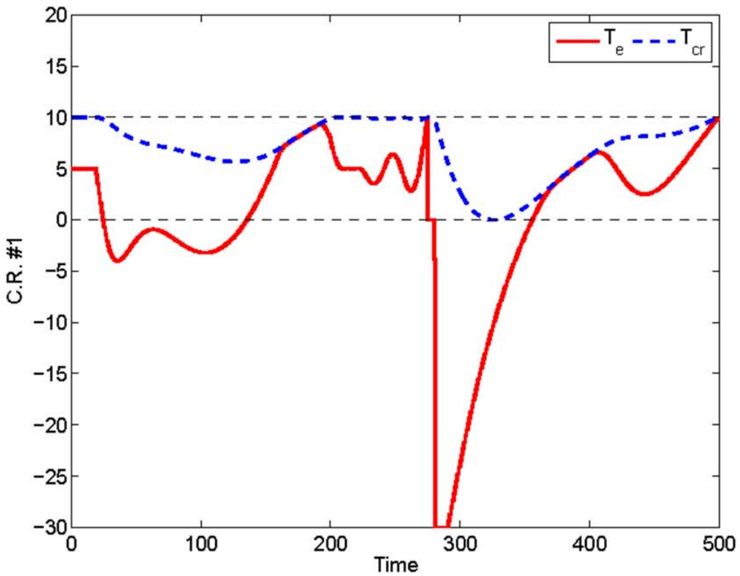


Power Management

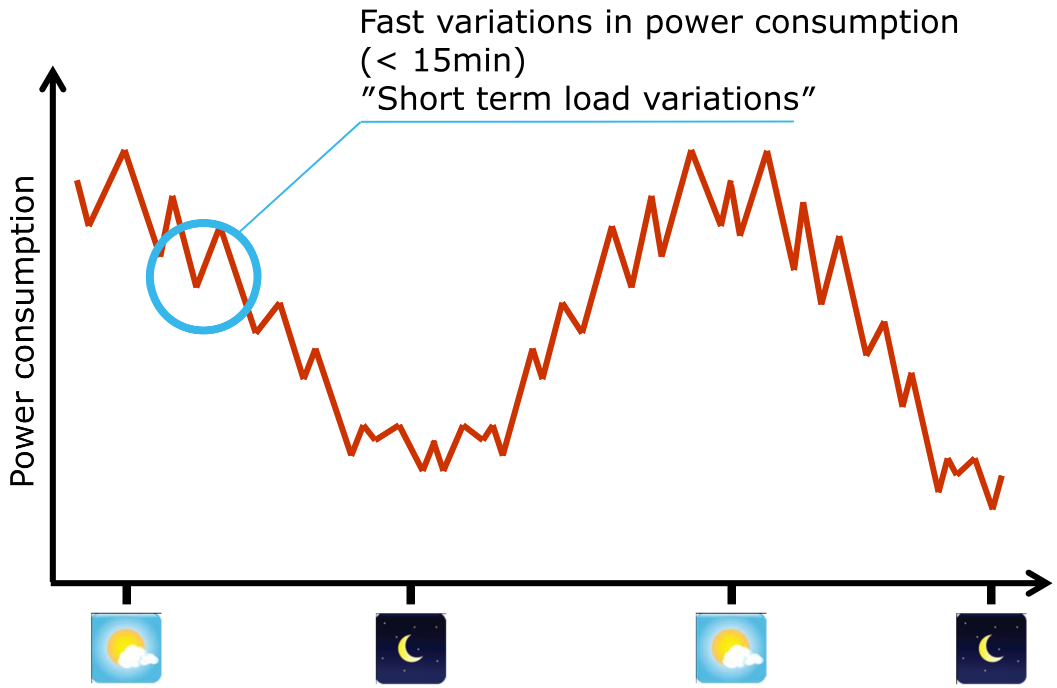
Example: Smart Grid (Flexible consumption).

Economic Model Predictive Control (MPC) demonstrated on power distribution portfolio including a cold storage with flexibility.
Presented at CDC 2010.

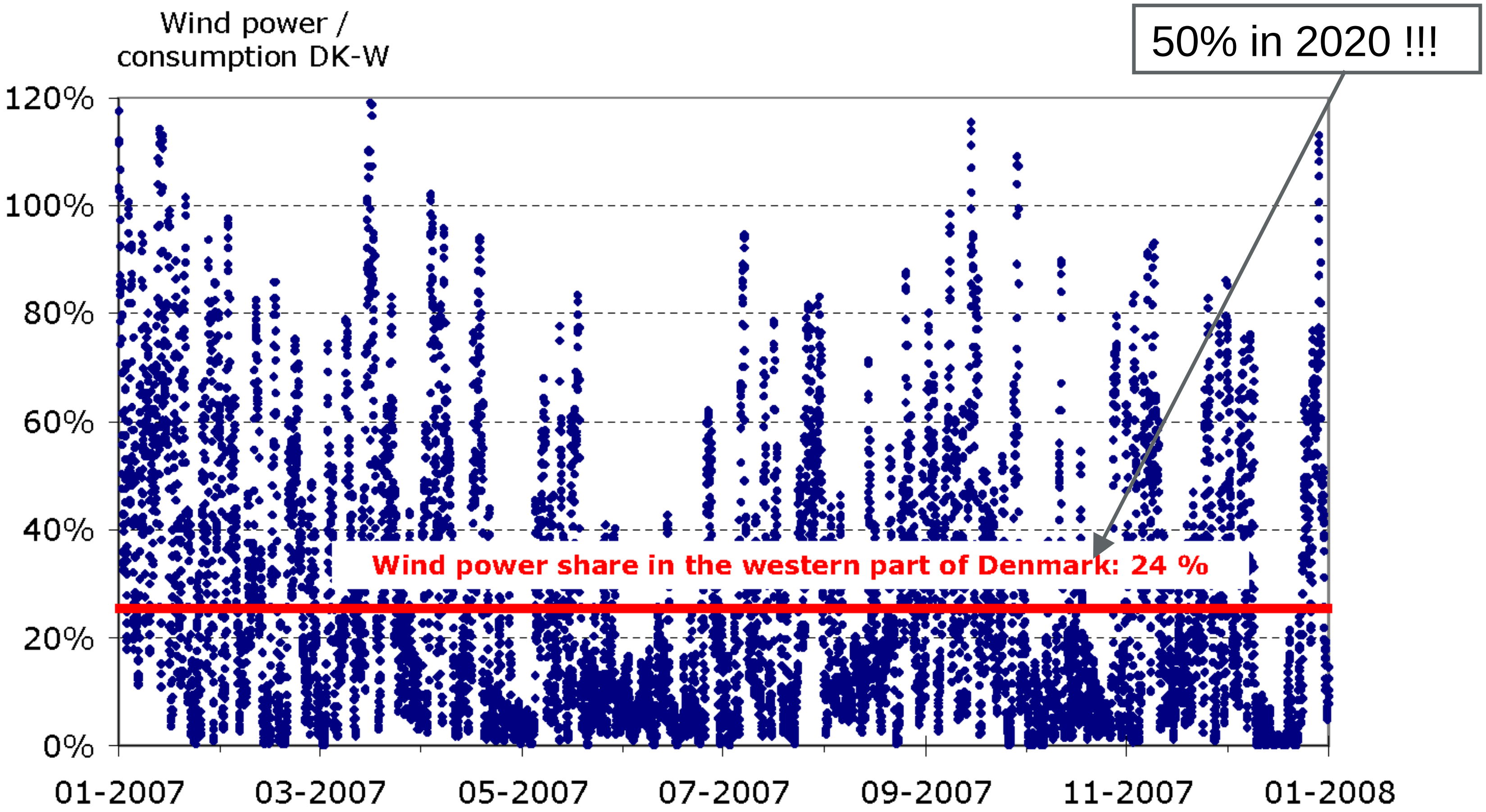




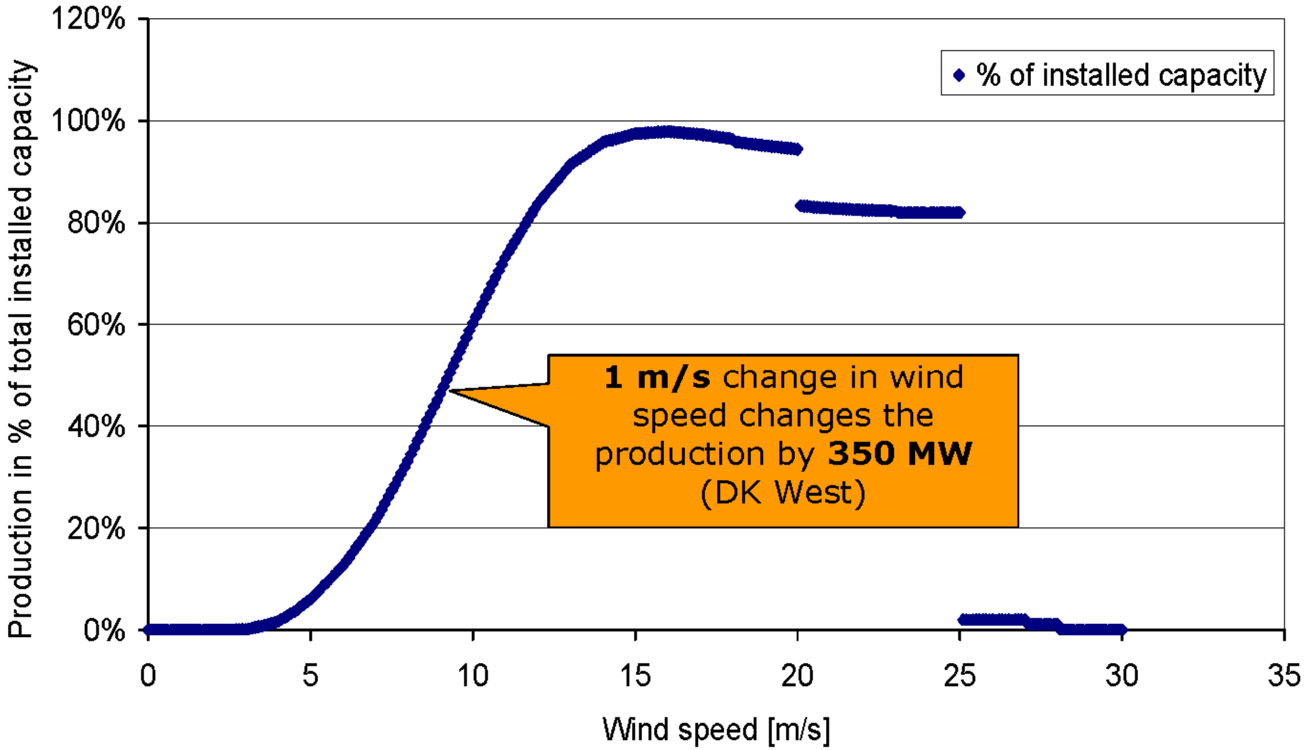
Power Management



Challenge and Motivation



Challenge and Motivation



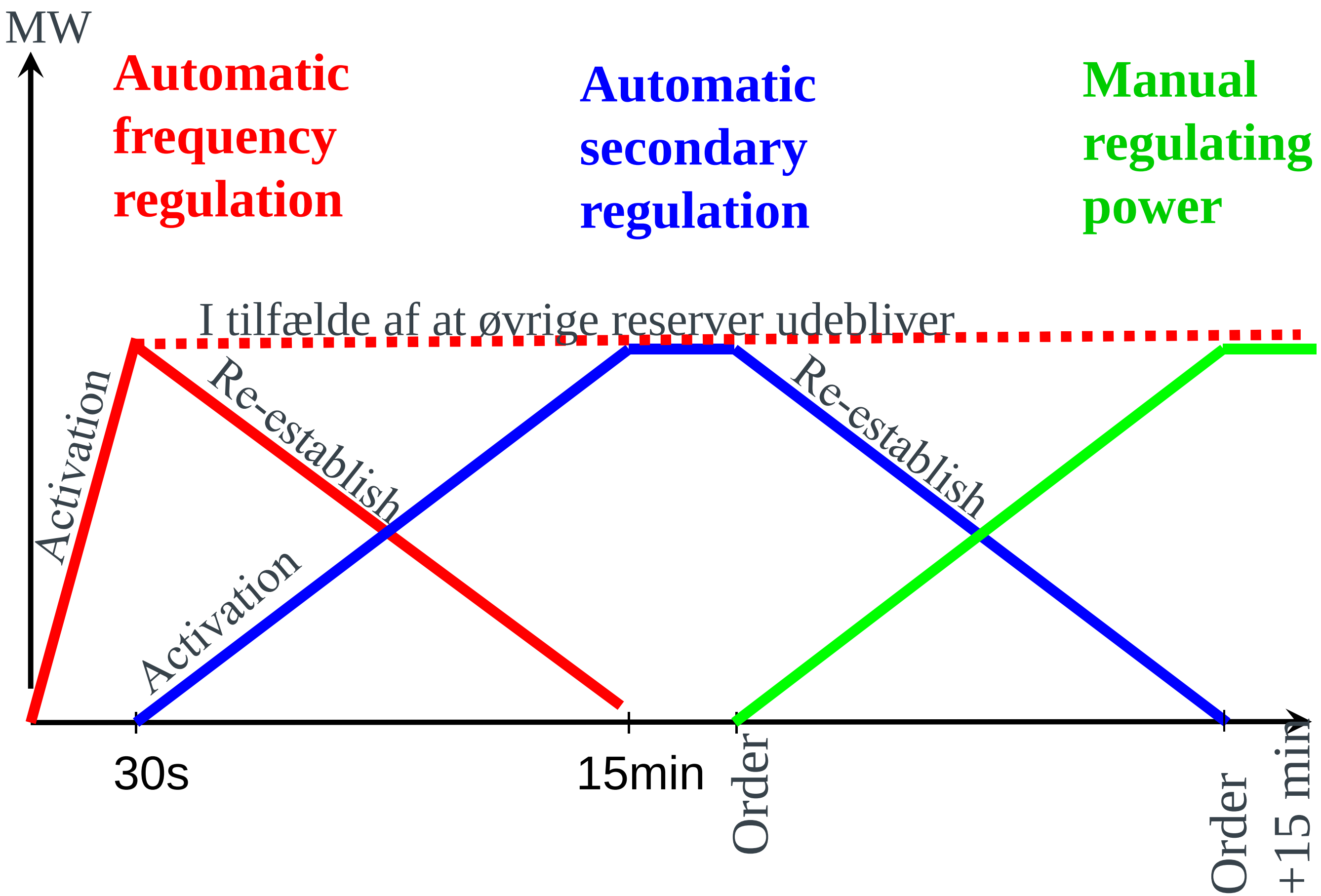
Regulating Power

A brief introduction:

- Ancillary service in order to balance production and consumption (stabilize frequency)
- Up-regulating power: increased production or decreased consumption
- Down-regulating power: decreased production or increased consumption
- Different types (amounts, activation times, automatic/manual)

Regulating Power

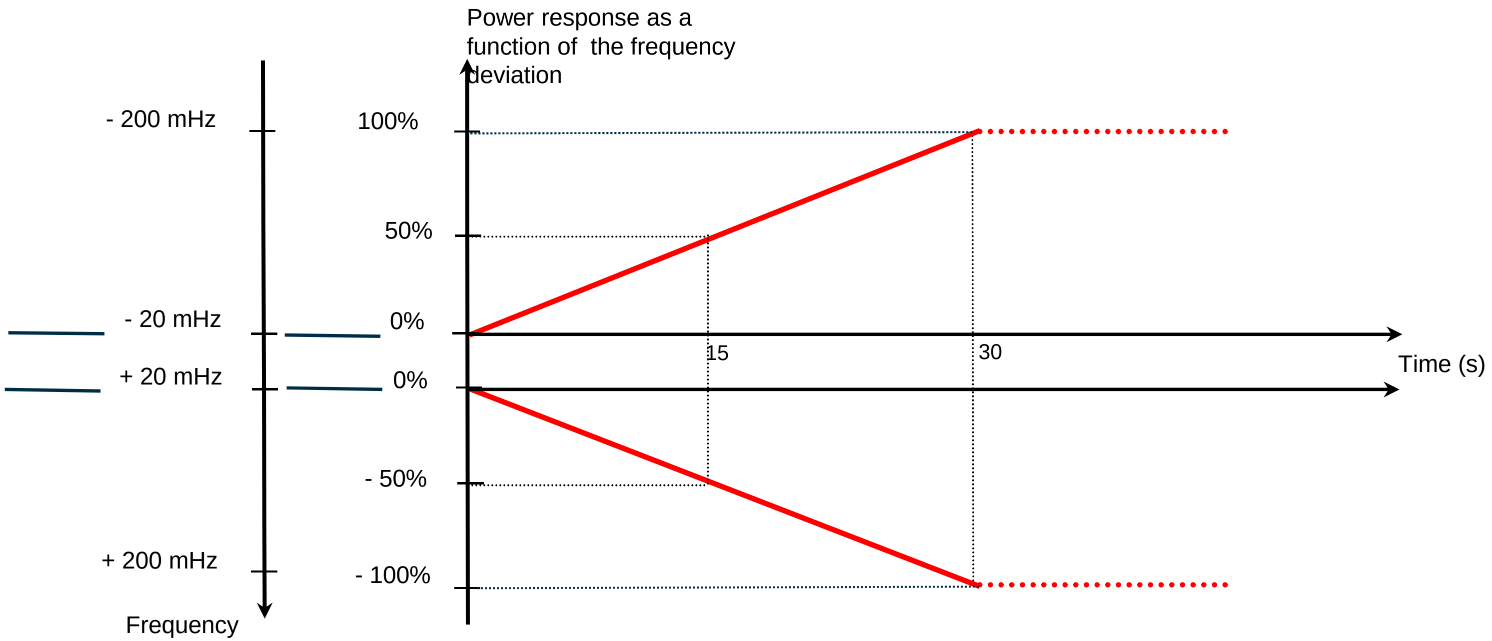
A brief introduction:



Regulating Power

Primary regulation:

- Automatic frequency dependent activation
- Uphold activated capacity for 15 min, re-establish in 15 min.
- No extra payment for activated power
- Availability payment independent of actual activation (non-symmetric up/down)



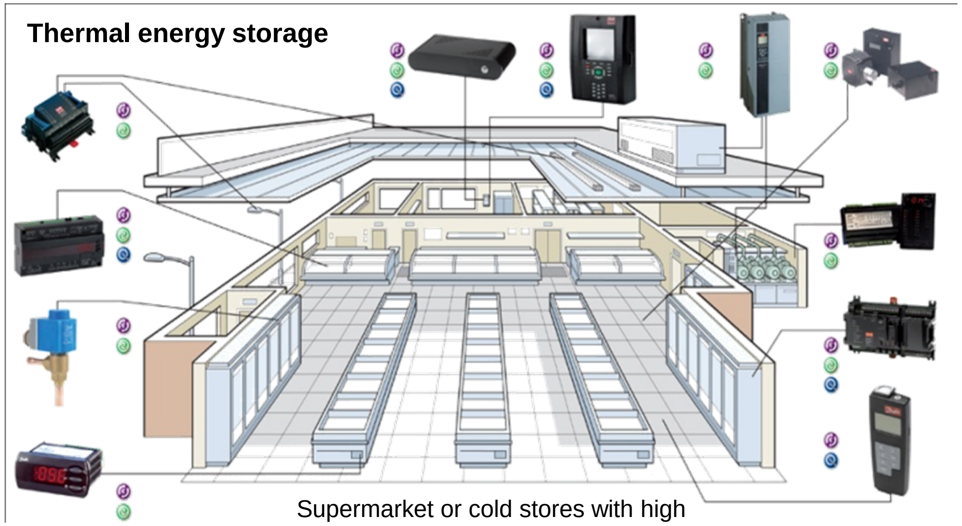
Supermarket Refrigeration

Flexible consumption with intelligent load-shifting and scheduling by storing energy in the form of “coldness”:

1. Utilize thermal mass in e.g. stored goods in supermarkets.
2. Food temperatures allowed to vary within defined limits.
3. Our studies reveal electricity cost savings up to 30%.

But:

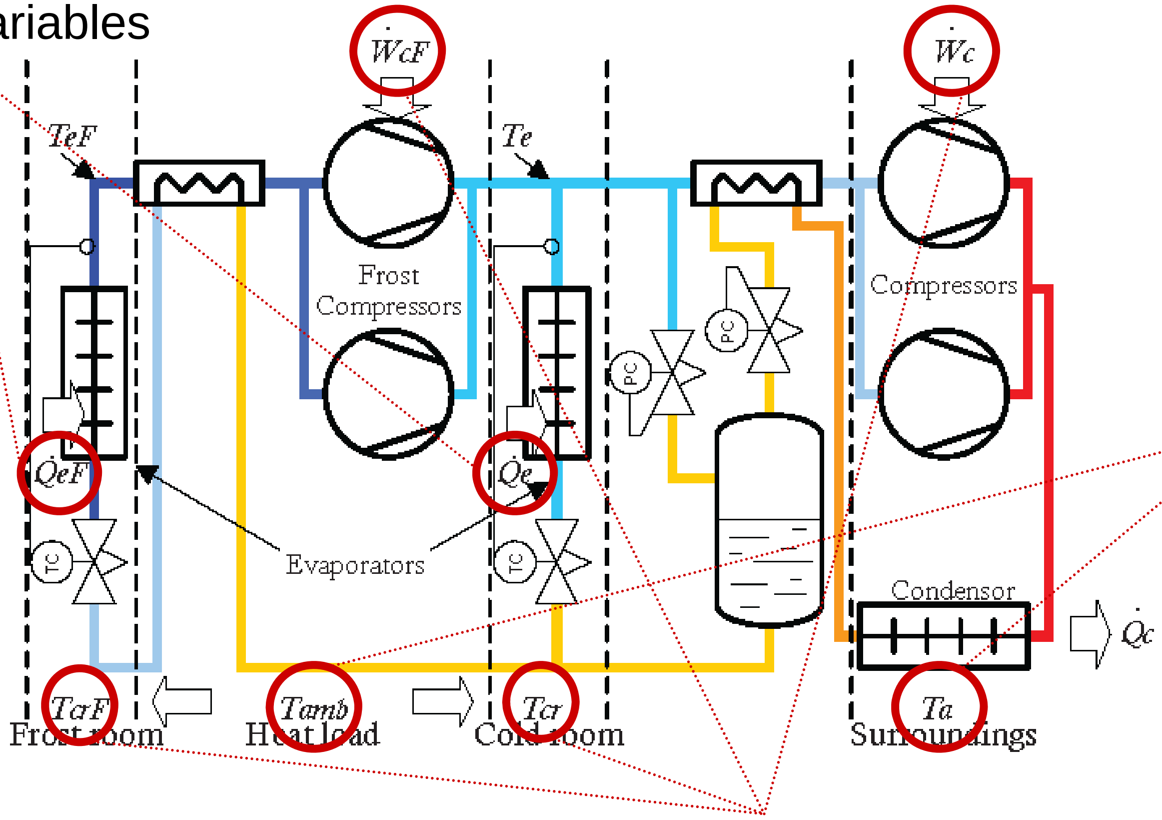
1. Food temperatures unknown!
2. Vast variety of systems!
3. Little computational power!



Supermarket or cold stores with high degree of HVAC & thermal storage capacity

Supermarket Refrigeration

Control variables



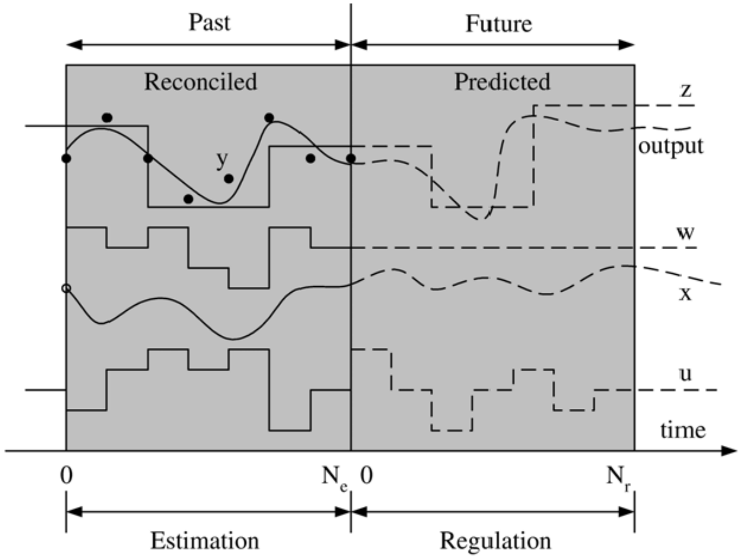
Disturbances

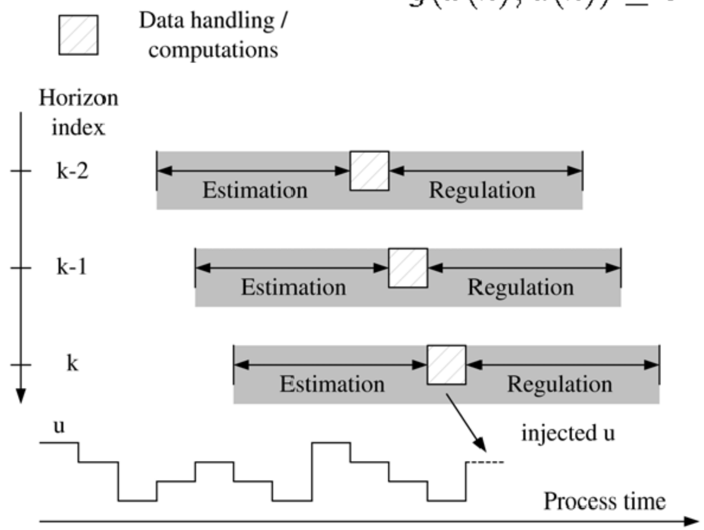
Economic Model Predictive Control (MPC)

Controller cost function: $$\Phi\left(x,\mathbf{u}\right)=\sum_{k=0}^{N-1}L(x(k),u(k))$$

- With e.g. for regulation: $$L(x,u)=\frac{1}{2}\left((x-x_{sp})'Q(x-x_{sp})+(u-u_{sp})'R(u-u_{sp})\right)$$

MPC Control problem: $$\min_{\mathbf{u}}\ \Phi(x,\mathbf{u})\ \text{, s.t.}\quad \begin{aligned}&x(k+1)=Ax(k)+Bu(k)\\&k=0,\dots,N-1\\&g(x(k),u(k))\le 0\end{aligned}$$





Method

Economic Model Predictive Control (MPC)

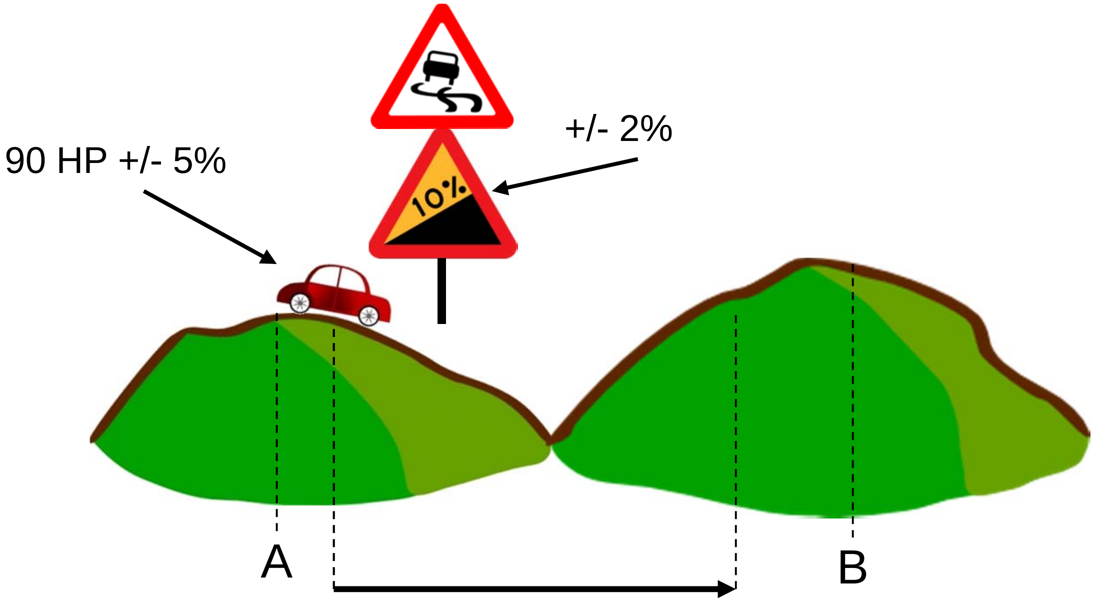
- Solve an optimization problem at each sample.
- Minimize an economic objective related to operation of the system.
- Repeat in a receding horizon manner

+ Incorporates predictions of future prices, temperatures, etc.
+ Handles constraints naturally.
+ Intuitive formulation of the cost of operation into a control problem.

- Relies on a model of the system and predictions of the disturbances.
- Can involve quite complicated numerical optimization problems.

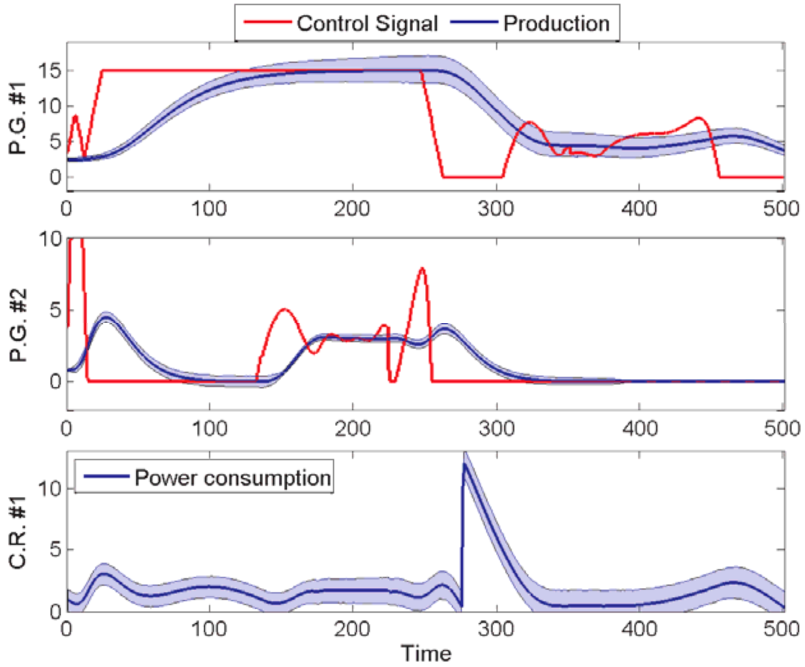
Example: Uncertain predictions and models.

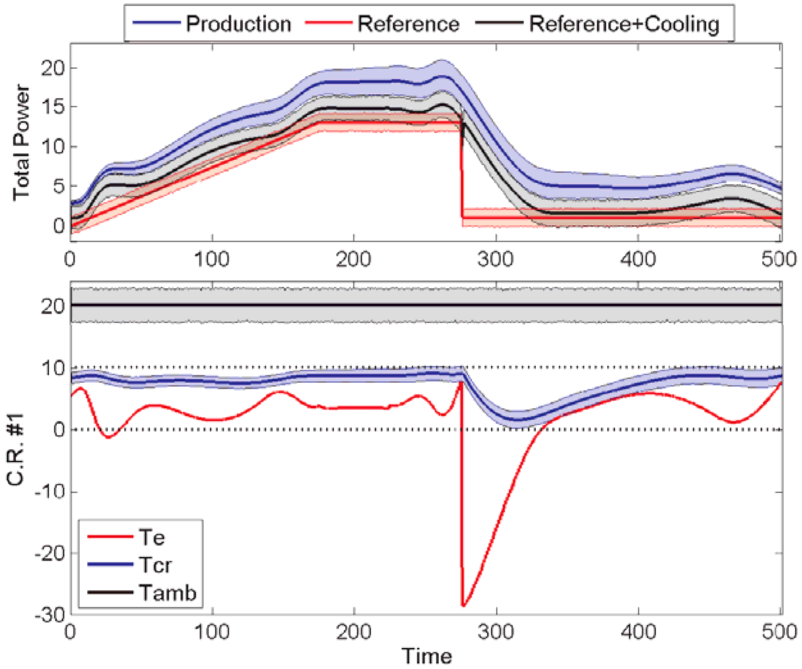
- Example: Drive from A to B with minimal fuel consumption. Stay on the road!



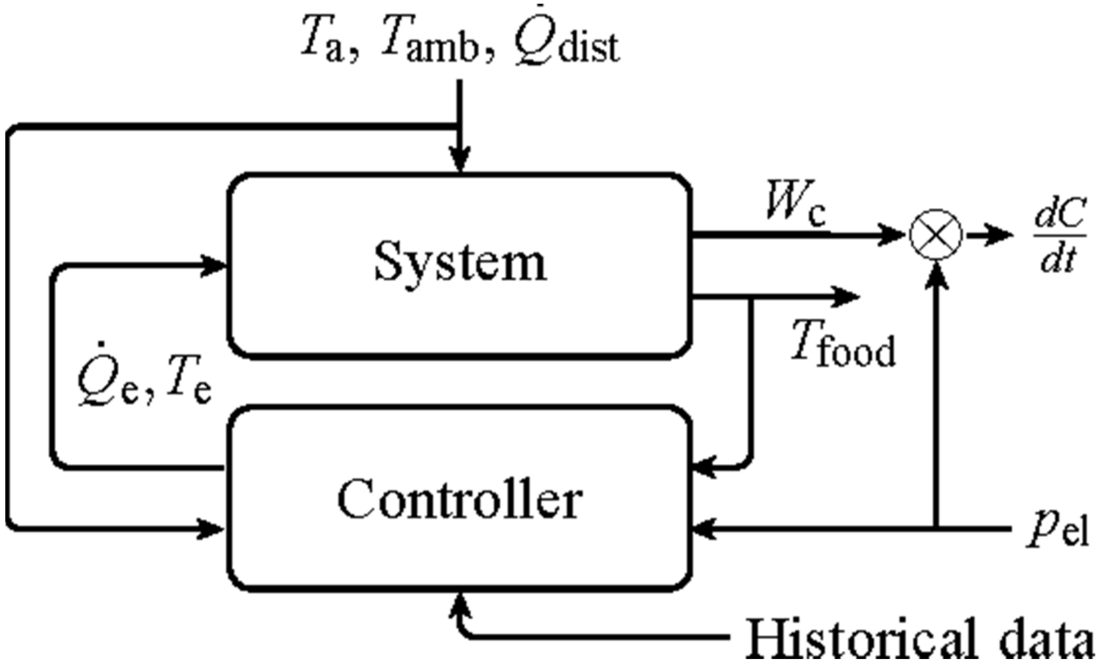
Example: Uncertain predictions and models.

Second Order Cone Programming (SOCP) for uncertainties in Economic MPC problems.
Presented at CDC-ECC 2011





Overall setup



Results

Simulations:

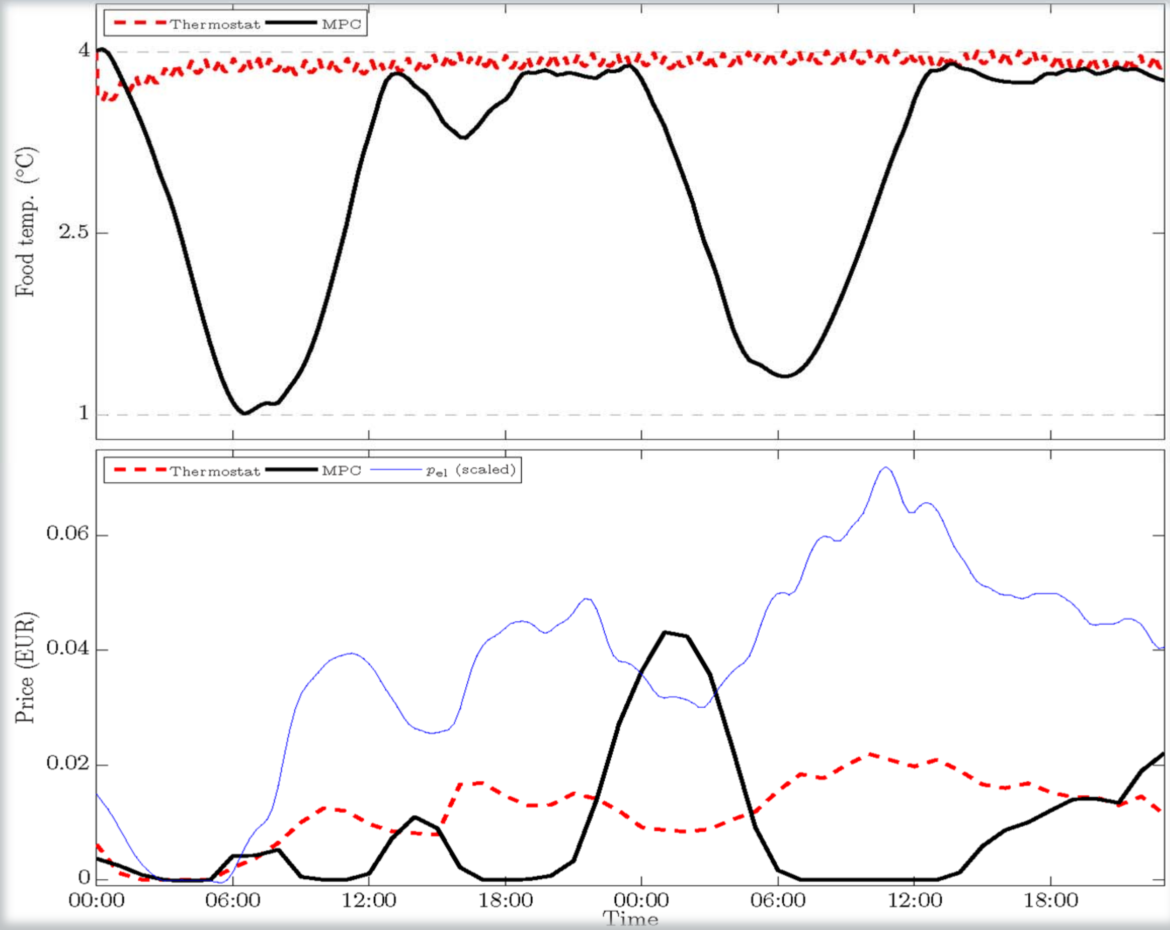
- Covering a full year (2010).
- Outdoor temperature from Denmark.
- Electricity prices from Nordpool.
- Uncertain heat load disturbances and thermal masses.
- Verified models from supermarket in operation in Denmark.

Implementation:

- Optimization problem solved iteratively
- Ultra fast solvers for real-time implementation.
- Soft constraints and back-off for robustness.
- Predictors trained on historical data (previous three years).

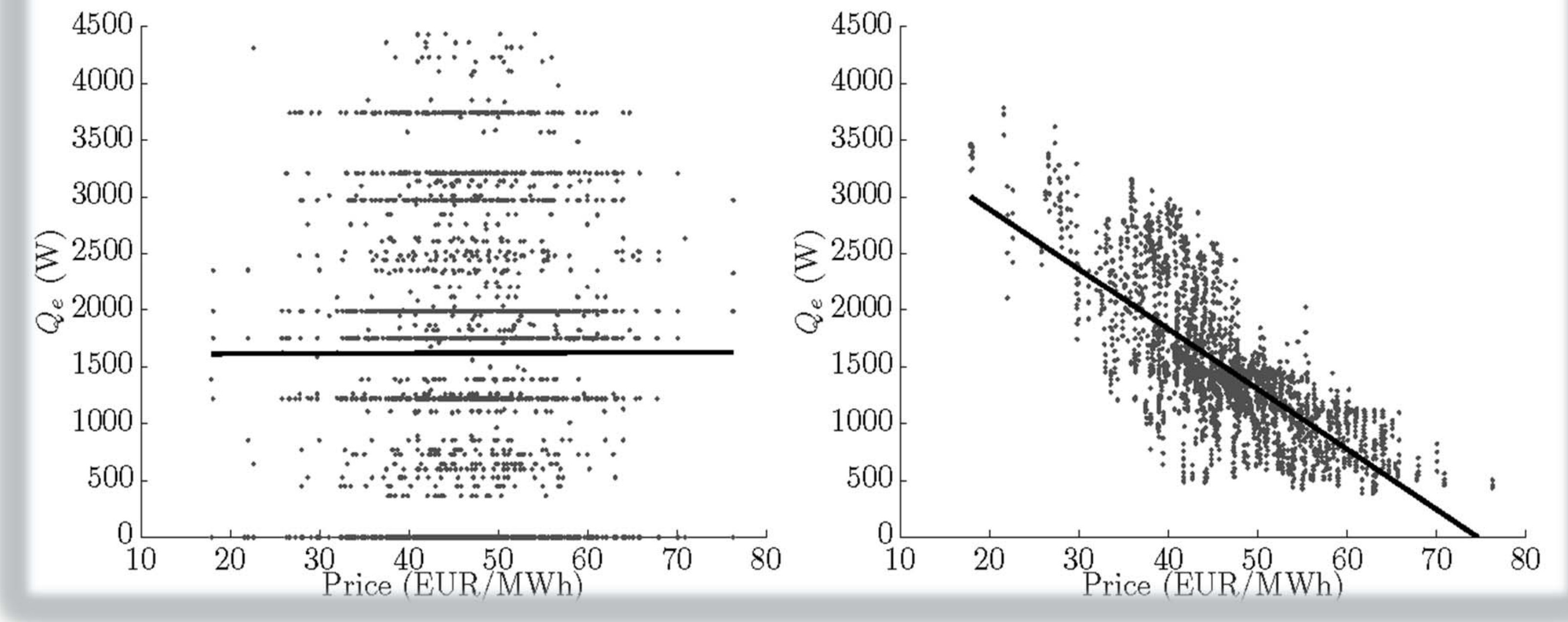
Results

Temperature profile



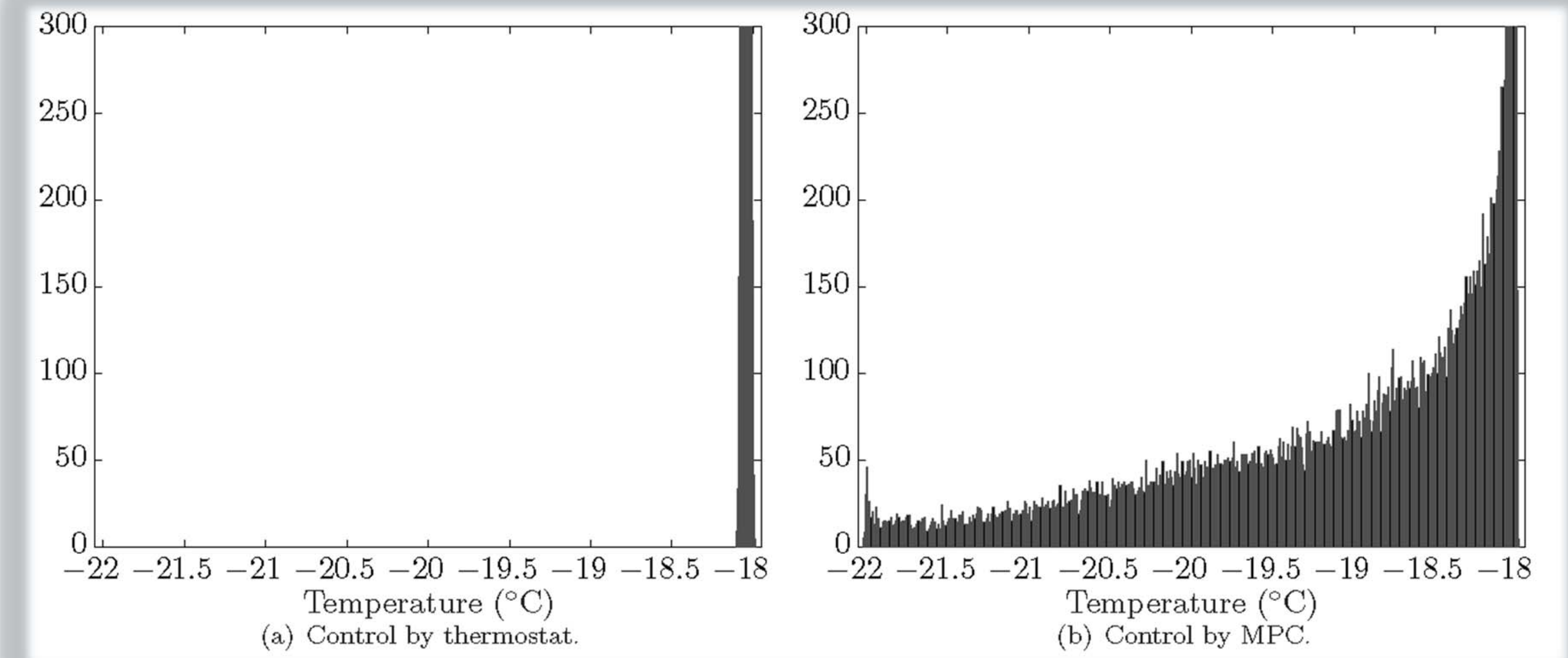
Results

Demand response



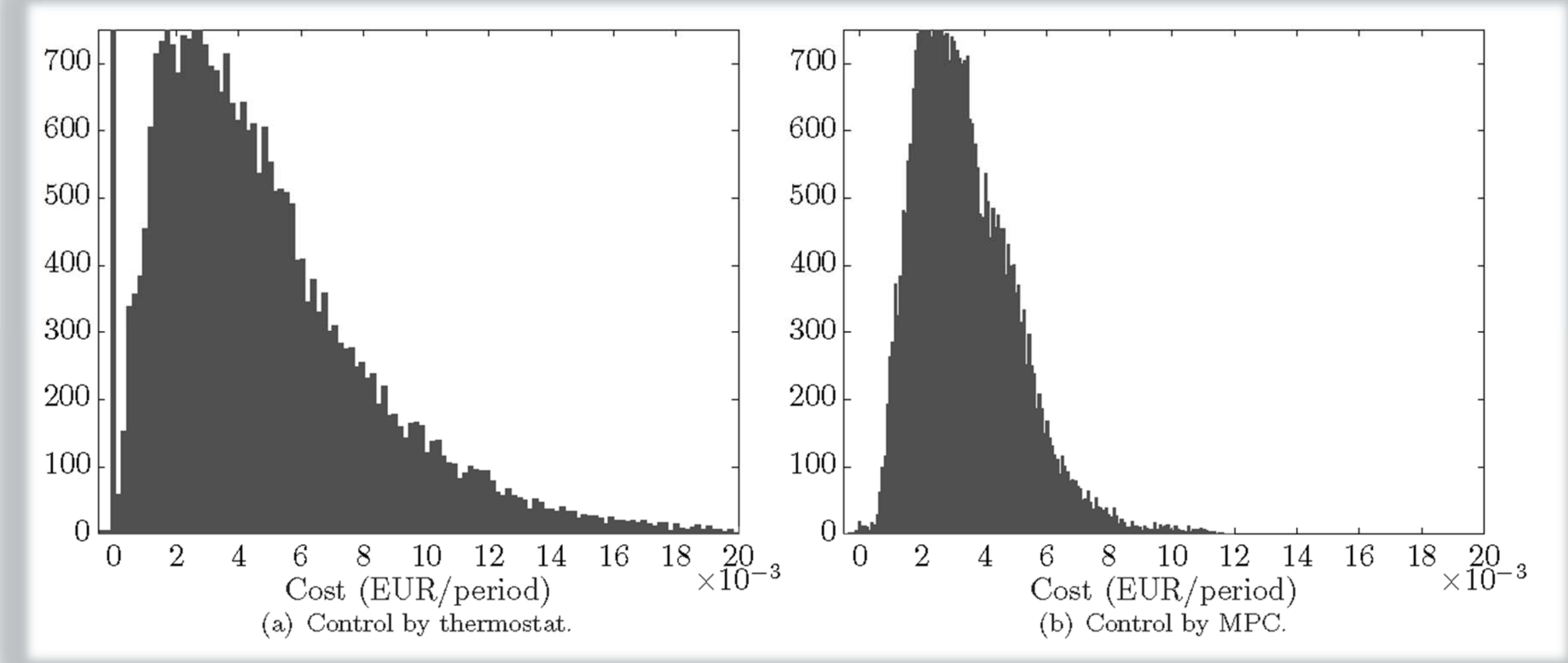
Results

Temperature distributions



Results

Price distributions



Results

Key findings:

- Cost savings around 30 %
- Potential for additional savings by offering regulating power.
- Very simple predictors are sufficient.
- Prescient simulation improves total cost with less than 2%.
- Closed-loop performance is quite robust against variations in model parameters.

Other results

Additional results include:

- Robustness investigations:
  - Advanced method with known probability distributions for the uncertainty.
  - Simpler version with back-off tuned to make constraint violations very infrequent.
- Modeling of dynamical systems for optimization and MPC purposes.
- Analysis of “active thermal mass” in foodstuffs.
- Experiments, identification, and validation on real systems in the lab.
- Investigation of optimization methods for industrial applications:
  - Standard linear and non-linear solvers.
  - Simplified problem formulations for linear solvers.
  - Dedicated fast embedded optimization techniques.

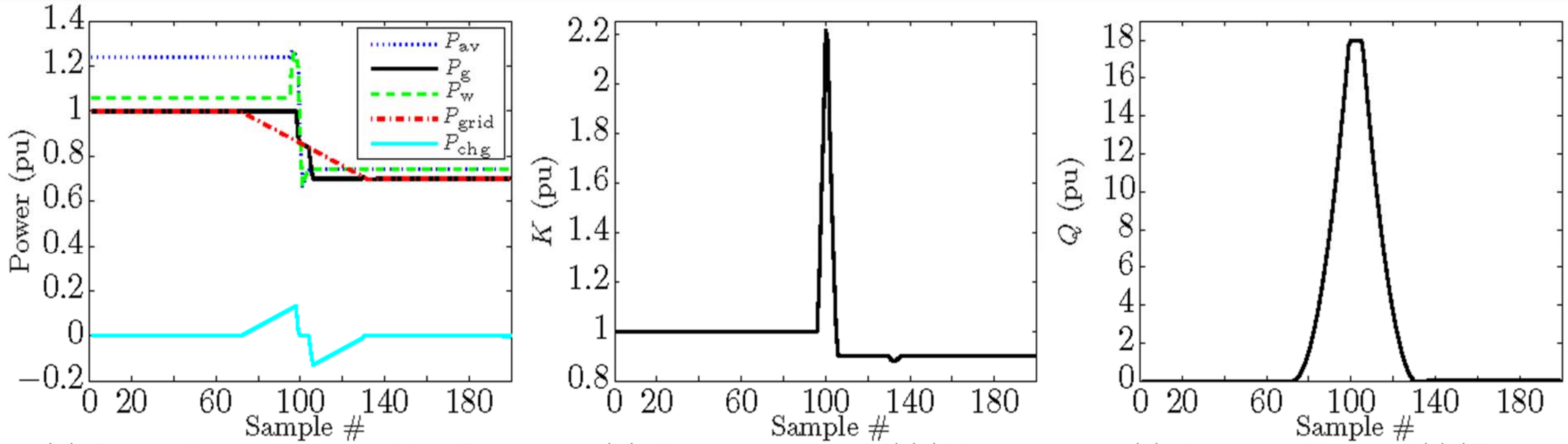
Connecting to wind power

Co-control of wind power plant and flexible power consumers:

- We prove a potential for combining
  - wind speed forecasts,
  - control of wind turbines
  - and control of flexible power consumers (e.g. chains of supermarkets).
- Goals:
  - Improve integrability (grid friendliness) of wind power to the grid.
  - Obey tight grid codes.
  - Reject disturbances from wind speed changes with minimal power loss.
  - Avoid expensive energy storage solutions.

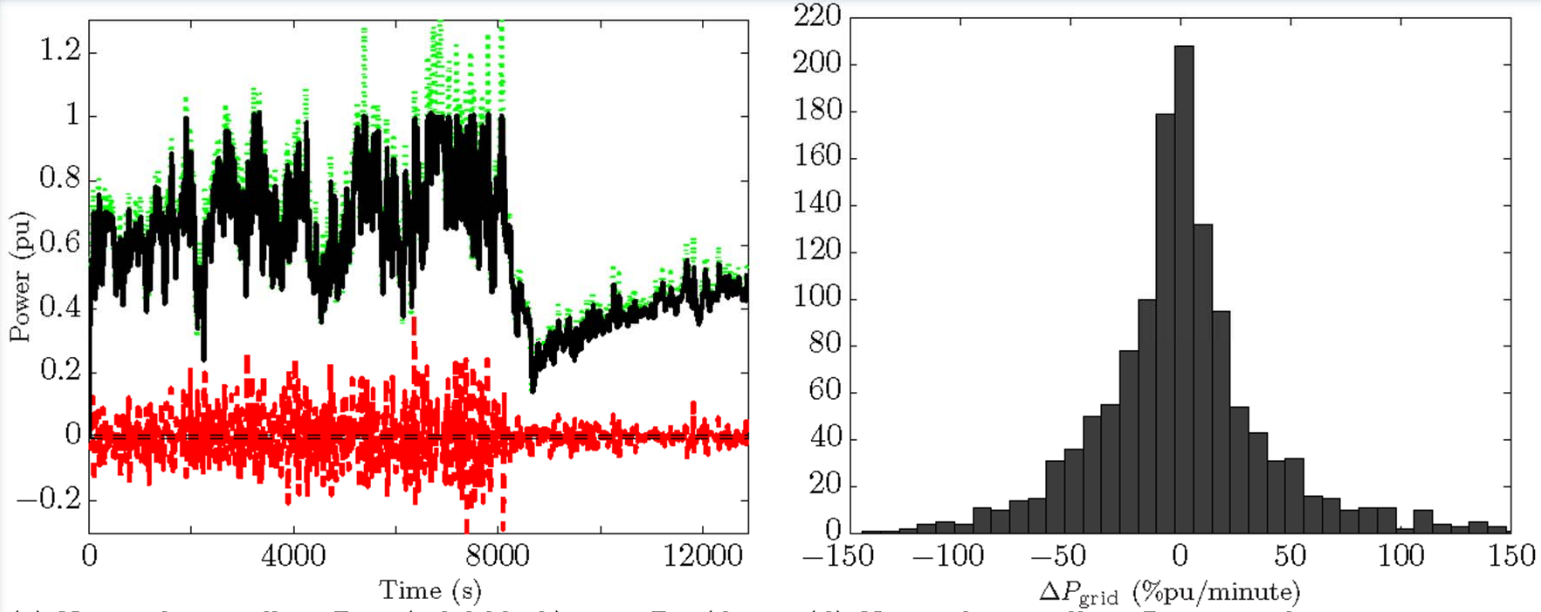
Connecting to wind power

Co-control of wind power plant and flexible power consumers:



(a) Power flows normalized by P_{rated}. (b) Kinetic energy, $K(t)/K_{\mathrm{rated}}$. (c) State of charge, $Q(t)/P_{\mathrm{rated}}$.

Co-control of wind power plant and flexible power consumers:

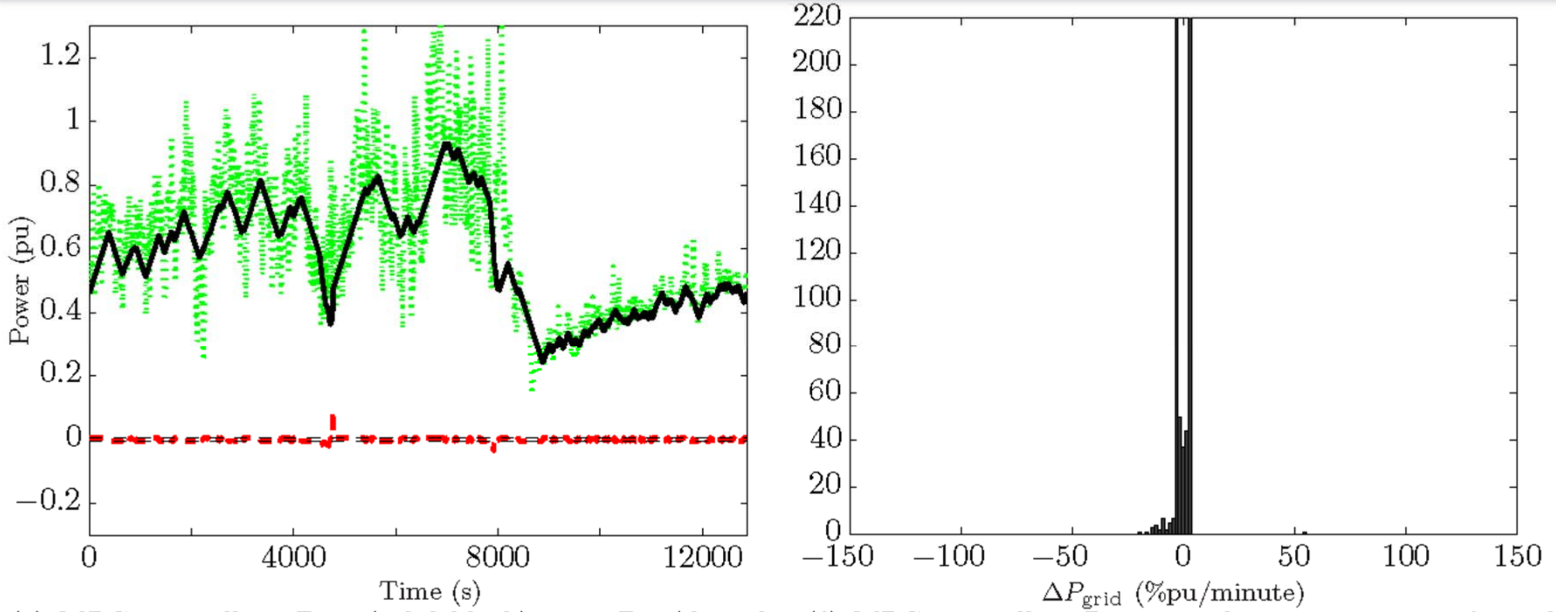


(c) Nominal controller: P_{grid} (solid black), max P_{av} (dotted green), and ΔP_{grid}/sample (dashed red).

(d) Nominal controller: Power gradient in per cent of rated power per minute.

Nominal controller with real wind scenario

Co-control of wind power plant and flexible power consumers:



(e) MPC controller: P_{grid} (solid black), max P_{av} (dotted green), and ΔP_{grid}/sample (dashed red).

(f) MPC controller: Power gradient in per cent of rated power per minute.

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MPC controller with real wind scenario

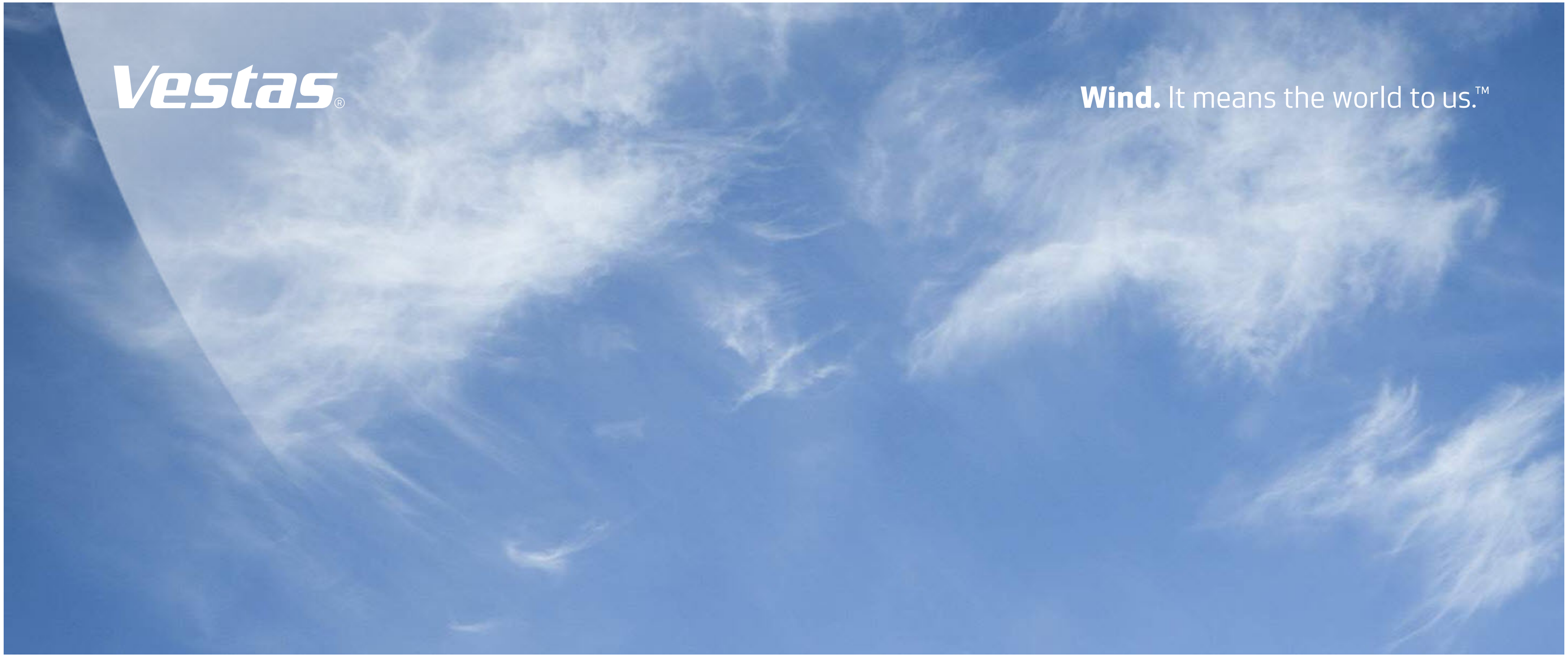
Conclusions

Findings in project:

1. Investigations and proof-of-concept for flexible power consumption in industrial refrigeration by use of Economic MPC.
2. Enabling load-shifting strategies and regulating power services with significant cost reductions.
3. Challenges in MPC for industrial systems tackled:
   - Model accuracy, computational load, predictions, etc.
4. Synergy and co-control potential with wind energy revealed.

Some selected references:

1. Hovgaard, T.G., Larsen, L.F.S., Edlund, K. and Jørgensen, J.B. (2012). *Model predictive control technologies for efficient and flexible power consumption in refrigeration systems*. Energy 44(1), 105-116.
2. Hovgaard, T.G., Larsen, L.F.S., Jørgensen, J.B., and Boyd, S. (2013). *Nonconvex model predictive control for commercial refrigeration*. International Journal of Control. In press. http://www.stanford.edu/~boyd/papers/noncvx_mpc_refr.html
3. Hovgaard, T.G., Boyd, S., and Jørgensen, J.B., (2013). *Model predictive control for wind power gradients*. Submitted to: International Journal of Control. http://www.stanford.edu/~boyd/papers/wind_gradients_cvx.html



Thank you for your attention
Questions?

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